CINEFORUM
ISSN: 0009-7039
Vol. 66. No. 6, 2026 (Special Issue 6)

Sustainable façade material systems for high-rise buildings: A structured review of operational energy, comfort and embodied-carbon evidence

Akshay Joshi,[1] Vikas Gulia[2*]

[1]Symbiosis Skills and Professional University, Pune, India
[2]Symbiosis Institute of Technology, Symbiosis International (Deemed University), Pune, India
***Corresponding Author**
Vikas Gulia
Symbiosis Institute of Technology, Symbiosis International (Deemed University), Pune, India
Email: vikas.gulia@sitpune.edu.in

HIGHLIGHTS

- Six façade material systems used on high-rise buildings were reviewed against peer-reviewed evidence.
- Reported energy savings vary widely, mostly with climate and the chosen reference case.
- Double-skin and lightweight membrane façades can raise cooling demand in hot climates.
- Façade benefits from ventilated cladding come from the cavity, not the tile material itself.
- Embodied carbon and circularity must be weighed alongside operational energy savings.

ABSTRACT

For high-rise buildings, the facade material selection is frequently based on the energy-saving, comfort and sustainability claims made by the manufacturers and trade-media. This paper looks at the extent to which such claims can be backed by peer-reviewed evidence for six popular façade systems: textile and membrane skins, double-skin façade, electrochromic glass, ceramic and terracotta ventilated façade, and external solar shading. The nine search strings were used in the Consensus academic search engine to conduct a structured literature review. Among 175 unique records, 70 studies were included and 27 studies reported operational-energy outcomes that were comparable. Energy savings reported varied from 20% up to 63% when compared to a reference case established for each of the studies. The difference in each system is as great as the difference between systems, and climate is the primary cause of it, with orientation, window-to-wall ratio and the performance of the reference façade being secondary. With regards to the performance in temperate and cold climates, the double-skin and lightweight membrane façade solutions proved to be good, but in hot climates, they were prone to overheating unless the cavity ventilation and shading were planned specifically. The energy benefit in ventilated ceramic and terracotta cladding was not because of the insulating properties of the cladding material but because of the outer insulation and the ventilated cavity. Some gains in operational carbon were often being undermined by embodied carbon, especially for aluminium intensive and double layer systems. A multi-criteria evidence matrix and climate specific selection guidance is suggested. The review findings are that none of the façade materials are sustainable on their own but that the sustainability of the materials is dependent on the climate fit, detailing, control strategy and whole-life carbon accounting.

Keywords: façade materials; high-rise buildings; double-skin façade; electrochromic glazing; ventilated façade; solar shading; embodied carbon; thermal comfort

1. INTRODUCTION

The façade is the surface that is the point of contact between a building and its external environment, through which it flows with the external world with respect to heat, light, air and sound. Façade choices have a significant impact on the energy demand for heating, cooling and lighting, on the comfort of the occupants, and on the whole-life carbon footprint of high-rise buildings, in which the façade-to-floor-area ratio is high, and exposure to solar radiation and wind is high (Aksamija, 2013; Echenagucia et al., 2022). With the energy codes becoming stricter, embodied impacts of façade materials, which have short replacement cycles and highly material intensive assemblies, are increasing portion of the whole-life emissions (Alabdulrazzaq et al., 2026; Cheong et al., 2024).
The focus of façade practice has shifted from load-bearing stone, brick and earth to light, layered and ever adaptive systems. These include membrane and textile skins, double-skin glass façade, switchable glazing, ceramic or terracotta rain screen cladding and fixed or kinetic shading (Shafaghat et al., 2022; Tabadkani et al., 2020). They are both sold as “sustainable” or “energy-efficient”. In the design profession, these claims are often introduced by architects via manufacturers' literature or trade portals and blogs, and not through peer-reviewed studies. A systematic review of intelligent façade performance revealed that in general, the economic and environmental performance of intelligent facades is less than their social and comfort performance, while there is little evidence

OPEN ACCESS © CINEFORUM

available (Habibi et al., 2022). The double-skin façade has also been used in a few double-skin façade case studies, which have shown very wide variations in operational-energy results and few life-cycle data (Pomponi et al., 2016).

Thus, there is a gap between the claims that guide the selection of the façade and the evidence that should guide the selection of the façade. The multi-criteria techniques used to design façades have been developed and are becoming mature (Bianchi et al., 2024; Moghtadernejad et al., 2018) but they rely on the reliable performance inputs of the different candidate systems. This study aims to close this void for six different façade systems that are frequently used in high-rise buildings. It poses three research questions:

What is the evidence from peer-reviewed sources for the operational energy performance and comfort performance of each system and in what conditions?

What is the difference between the sustainability case of each system in terms of embodied carbon, durability and circularity?

What common claims are supported, conditional or unsupported and what guidance can be given to the designers?

2. METHODOLOGY

2.1. Review design

A systematic literature review was conducted. It was based on the methodology of a systematic review (defined search, screening and extraction) carried out using Consensus, an AI-powered academic search engine, which indexes peer-reviewed records from Semantic Scholar, Scopus, PubMed and arXiv.

2.2. Eligibility and screening

Records were included if they met three criteria:

They were published journal articles, conference papers or scholarly books that had been peer-reviewed.

They measured, simulated or life-cycle performed a façade system or façade material, either at component, room or building scale.

They dealt with one of the six systems or with a cross-cutting issue (embodied carbon, circularity, multi-criteria selection).

Records that did not focus on materials that form building envelopes (e.g. industrial membrane processes), structural/mechanical characterisation only or systems not relevant to this review were excluded. For example, there is a significant amount of evidence for green façades (Sheweka & Mohamed, 2012), which were not included. Five duplicates were removed and 175 unique records were screened by title and abstract. Seventy studies were included (Figure 1). Twenty-seven of these reported an operational-energy outcome (total, primary, HVAC or cooling energy) as a percentage change from a stated reference case. The following were removed for quantitative comparison.

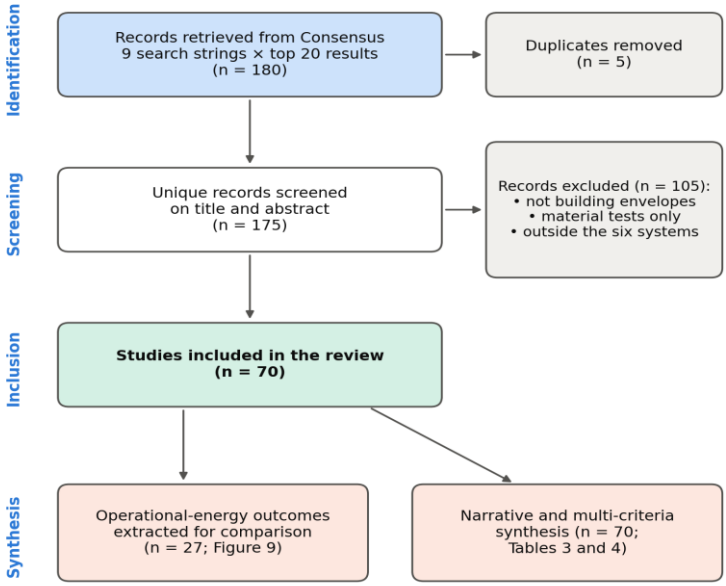


Figure 1. Flow diagram of the structured literature review.

OPEN ACCESS © CINEFORUM

2.3. Data extraction and synthesis

The following was extracted for each of the included studies:
façade system and configuration,
climate or location,
The methods used were simulation, experiment, field monitoring or life-cycle assessment,
reference case,
performance outcomes (energy, cooling load, thermal comfort, daylight, glare, embodied carbon or energy),
stated limitations.
Due to the disparities in metrics, baselines and climates across studies, no pooled effect size was calculated. The results are instead reported in ranges (Figure 9) and the type of the meteorological quantity and the climate are reported. The extent to which each system met each of the eight sustainability criteria were then scored in a qualitative multi-criteria matrix (Table 3), based on the criteria generally found in façade decision frameworks (Bianchi et al., 2024; Moghtadernejad et al., 2018).

3. RESULTS: EVIDENCE BY FAÇADE SYSTEM

3.1. Textile and membrane façades

Textile façades are either single layers of coated fabrics (PVC-coated polyester, PTFE-coated glass fibre) or a second skin in front of a conventional wall or curtain wall (Figure 2), or they are pneumatic cushions. They offer the most significant properties of lightness, material productivity and form-freedom. The life-cycle analysis of enclosures constructed of ETFE indicates that it can be environmentally effective only if minimum use of material is adopted and maximum efficiency of the components is achieved (Monticelli et al., 2020). The range of reported embodied energy values for ETFE from 26.5 to 210 MJ/kg is attributed to the variety of inventories used (Lamnatou et al., 2018). The cradle-to-grave comparison of these five options identified inflated ETFE systems as having the lowest overall environmental footprint while PVC tensile systems had high production impacts and end-of-life impacts (Bal et al., 2026).



Figure 2. Translucent fabric façade, Gardner Neuroscience Institute, University of Cincinnati, USA

Thermal performance is the main problem. The thermal inertia and insulation property of membrane envelopes are low (Tian et al., 2021). In sports halls, double-layer membranes used, and saved 11-18% of heating energy than the single-layer membranes (Suo et al., 2015). However, even for double layer systems the percentage of the occupants that were not satisfied was still above the conventional acceptance limits in all six climates tested (Ranđelović et al., 2026). Results are highly dependent on design as a second skin. In a refurbishment project of an office building in a southern Italian location, a PVC coated polyester second skin was installed to achieve the following energy savings: up to 6.1% (Ciampi et al., 2021). The primary energy consumption was reduced up to 35.1% in three European climates using a controlled operation tensile second skin (Mokhtari et al., 2023). In a southern Italian residential retrofit, a second 3D-printed and fabric skin helped to lower the cooling load by 30.2% and primary energy consumption by 16.4% (Spanodimitriou et al., 2025). Meshes applied selectively are shown to reduce the energy demand by up to 20% in London, while applying them uniformly raised the energy demand by 20% (Elhussein, 2025). A PTFE kinetic façade has been found to save HVAC energy in the composite climate of Jaipur by just 1.3% compared to a code-compliant HVAC system (Kuda et al., 2025).

OPEN ACCESS © CINEFORUM

So the statement of fabric façades "reflect solar heat" and being a "thermal jacket" in winter is really only true in the winter. The result will be determined by the openness factor, colour, stand-off distance, orientation and control. The solar radiation transmittance at normal incidence (T0) of metal and plastic meshes with high openness is in the range 40-70% (Mainini et al., 2022). The sometimes claimed cost savings with membrane installation have not been seen in the peer-reviewed literature reviewed here, and were not considered to be of the order of 50% or more.

3.2. Double-skin façades

A double-skin façade (DSF) consists of an additional outer layer of glazed or perforated surfaces placed in front of the main façade and separating the two to form a ventilated cavity (Figure 3, 4). Cavity can be ventilated naturally, mechanically or a combination of both and can be operated seasonally and throughout the day (Figure 4).

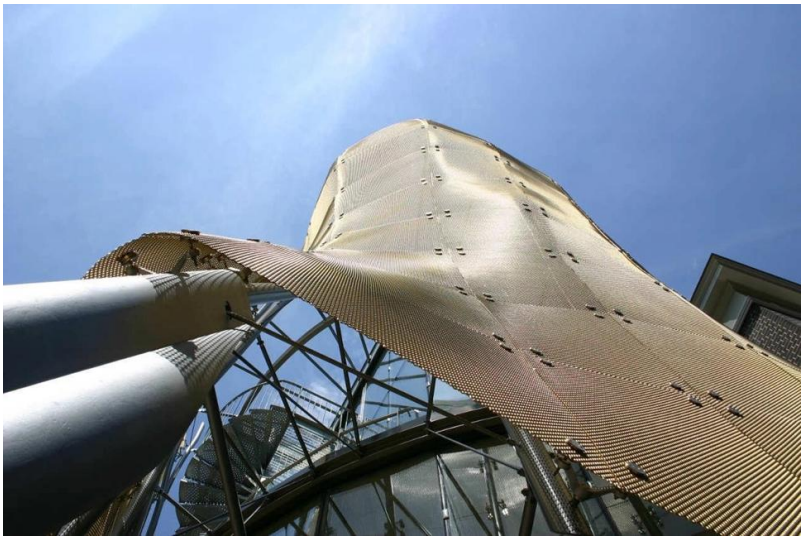


Figure 3. Metal meshed glazed structure, The Hague, the Netherlands.

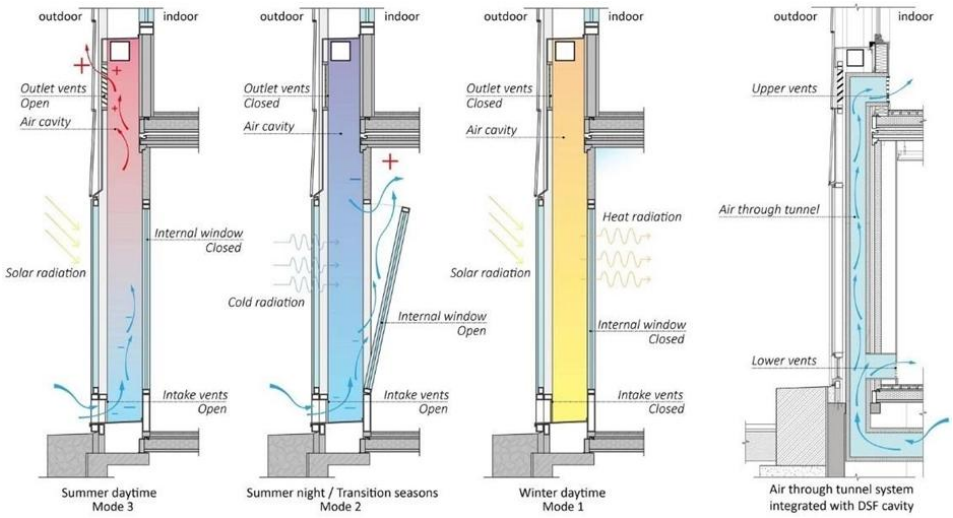


Figure 4. Modes of operation of a ventilated double-skin façade: summer daytime, summer night and transition seasons, winter daytime, and air supply by a tunnel system embedded in the cavity.

The DSFs were designed for cold and temperate climates where the cavity is used as a thermal buffer and preheats the ventilation air. The evidence is inconclusive in hot climates. The early simulation and monitoring in hot-arid conditions proved that a DSF can reduce heating costs in winter, but requires night ventilation and cavity shading to reduce cooling costs in summer (Hamza, 2007; Hashemi et al., 2010). Optimised DSF alternatives decreased the energy consumption by 7.9-14.8%, while the embodied carbon increased by 23.3-47% and the simple payback period over the building's 50-year life was calculated as longer than the building's life (Zomorodian et al., 2018).

OPEN ACCESS © CINEFORUM

A latticework DSF, in humid tropical Panama, overheated because of lack of cross-ventilation (Castillo-DR et al., 2026).
When cavity design is specified, there are significant savings to be had. In Dubai, the annual cooling energy is reduced by 22% in the naturally ventilated DSFs and by 32% for the mechanical cavity ventilated DSFs (Aldawoud et al., 2020). S. Naddaf et al. (2023) showed that in Erbil, SHF can still save 9-14% in cooling demand while OPT can save 35.7-42.3% in cooling demand of a high-rise office in Saudi Arabia (Said et al., 2026) and a three-façade DSF can save 53.5% cooling energy in a hot-summer Mediterranean climate (Ahriz et al., 2022). The added insulation was the best passive measure followed by combined passive measures which reduced cooling energy by 18.2% and the type of glazing and cavity width reduced by 1-2% (Rasoulbaghal et al., 2026) in a hot-arid DSF. In the case of high-rise offices in Tel Aviv, the wider the cavity, the lower the cooling loads became as it was increased from 0.2 m to 2.0 m (Saroglou et al., 2020). The narrow DSFs in Japan resulted in an increase of product-stage embodied carbon of approximately 33%, while the operational carbon decreased by 29-38%, resulting in a total emission of 33-38% lower (Srisamranrungruang et al., 2026). Despite the number of studies conducted in temperate climates, however, an overall picture of very scattered results and almost no life-cycle energy data was obtained from a meta-analysis of over 50 temperate climate studies (Pomponi et al., 2016).

3.3. Electrochromic glazing

Electrochromic (EC) glazing is able to shift between different visible and solar transmittance (Sbar et al., 2012) levels when a voltage is applied. It is increasingly applied to facades of high buildings, especially on the glazed ones as shown in figure 5.
The savings of simulations are consistently reported, with the size varying according to the baseline. In the 3 US climates, EC windows led to a 20% or greater reduction in building energy use when compared with code-compliant static glazing. There were also savings greater than 45% (Sbar et al., 2012) when compared to single pane static glazing. Other studies reported savings of 7-16% in Athens (Detsi et al., 2024), 17-23% in Dhahran (with control, Budaiwi, 2023), 14-36% in west-facing rooms in three European climates (Teixeira et al., 2024), up to 27% for dual-band EC glazing (Riganti et al., 2025), and 4.5-6.5% of the heating and cooling demand in Mashhad (Kamelnia et al., 2024).

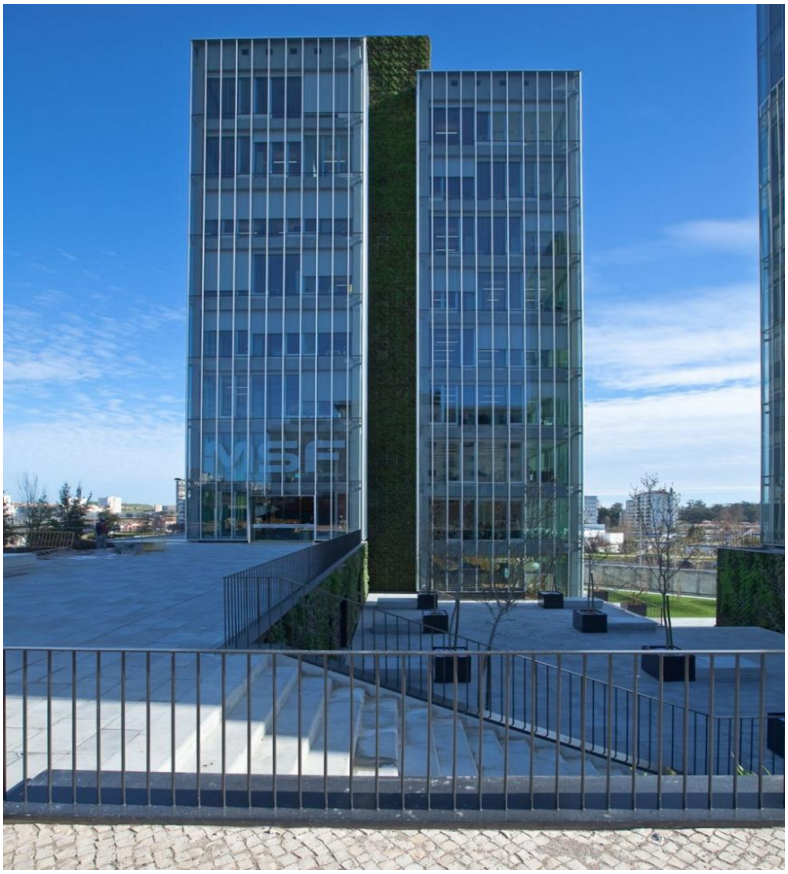


Figure 5. Glazed high-rise towers, Natura Towers, Lisbon, Portugal.

OPEN ACCESS © CINEFORUM

Savings were greater in the warmer and sunnier climates. The primary benefit of EC glazing was the reduction in cooling peak loads, while the predicted thermal discomfort (Dussault et al., 2017) was relatively unaffected. The control strategy is key (Jelle et al., 2019). The use of artificial lighting can be significantly higher when controlled by temperature (Teixeira et al., 2024). The occupant survey results of an office with an EC-glazed façade were found to be gloomy, a reminder that achieving energy efficiency does not equate to achieving satisfaction from the visual environment (Day et al., 2019).
The literature does not trace back to the up to 35% reduction in building energy consumption that is claimed for glass panels. The reduction of up to 35% in building energy consumption is only found in literature in a combined scenario. In Iranian high rise offices, up to 35.57% savings were achieved by using EC windows with optimum glazing and building-integrated photovoltaics and building energy management (Fathi et al., 2021). This should not be a glazing effect only.

3.4. Ceramic and terracotta ventilated cladding

The typical applications of ceramic and terracotta (fired clay) panels are on the outer leaf of an opaque ventilated façade (OVF): panels hang from a metal sub-frame in front of an insulated wall, leaving a ventilated cavity (Figures 6 and 7). The system is appreciated for its durability, low maintenance and fire resistance of the cladding itself, as well as for its aesthetic range (Pizzatto et al., 2025).

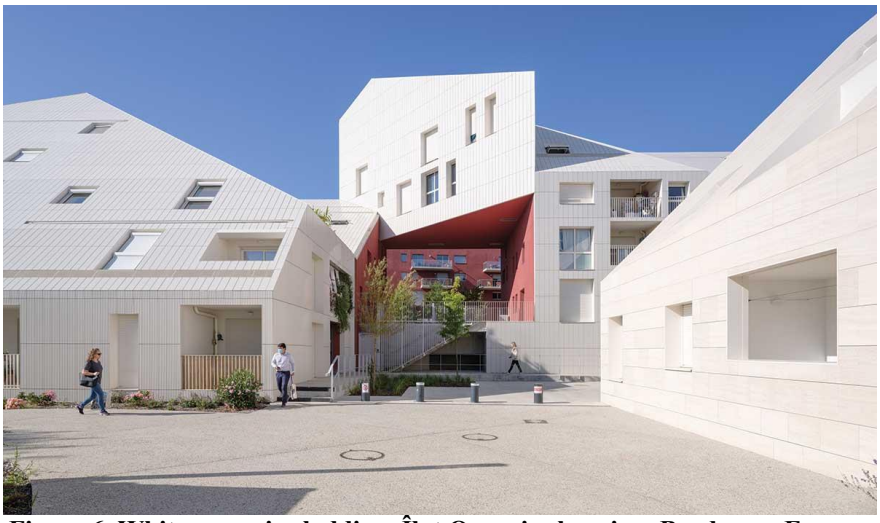


Figure 6. White ceramic cladding, Îlot Queyries housing, Bordeaux, France.



Figure 7. Terracotta (clay) ventilated façade.

It is well established that an OVF provides energy benefits. In the Mediterranean climate an OVF reduced the daily energy flux by 20-55% compared to an unventilated façade, mainly during the summer months, on the east and west exposures (Gagliano et al., 2020). The experimental hollow-clay OVFs were found to reduce solar heat loads by approximately 30-70%, depending on the configuration of the OVFs (Fantucci et al., 2020). The gains in electricity consumption in the hottest cities in Brazil were as high as 43% annually (Maciel et al., 2019). Domínguez-Torres et al. (2022) conducted an OVF with windows in Seville, which saved approximately 21% in

OPEN ACCESS © CINEFORUM

annual energy consumption. The summer and winter gains in the cold zone of China were 11.4% and 6.5%, respectively, (Lin et al., 2022). In the hot and humid Turkish climate, the interior heat transfer was cut by 40% compared to alternatives and open joint configurations, cut by 64% compared to an unventilated reference (Takva et al., 2026).
Mechanism is significant for material claims. Ceramic and fired-clay panels are not insulators; they are relatively conductive. Their contribution is from interception of solar radiation, reflectance (if light coloured) and from the stack driven ventilation of the cavity behind them. The ideal summer approach is to prevent heat from penetrating the outermost layers, by applying low-conductivity cladding and insulating the exterior side of the main wall (Roig et al., 2024). A thermal buffer can be created by the use of an external massive cladding layer (Stazi et al., 2020). Roig et al. (2024) also showed that the configuration with the lowest operational energy is not necessarily the best over the whole life cycle. The claims of ceramic or clay façade tiles being "excellent heat insulators" are therefore wrong in so far as they are made as such. Replace with evidence-based claim that a well-detailed ventilated cladding system lessens summer heat gains.

3.5. External solar shading

External shading devices (either fixed or movable louvres, fins, overhangs, egg-crates and kinetic or photovoltaic-integrated systems), block the solar radiation before it hits the glass as shown in figure 8. External shading is the system with the best documented evidence, and it is well known that this is beneficial over all latitudes (Palmero-Marrero et al., 2010). In Mediterranean offices, optimised fixed devices have resulted in 37-49% reduction in cooling energy with high performance glazing and ~ 33% reduction in total energy (Koç et al., 2021). Shading on a high-rise residential building in Seoul, resulted in a reduction of cooling energy of approximately 20% (Cho et al., 2014). The exterior louvres were perforated to reduce the energy use of the office space by 15-63% and still satisfy the visual-comfort requirements (Uribe et al., 2018).

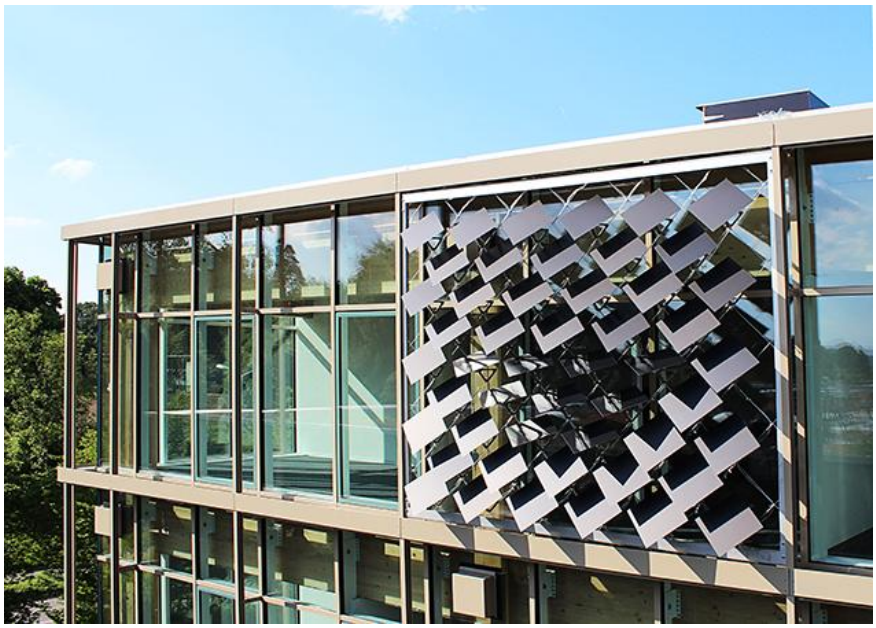


Figure 8. Adaptive solar façade, HiLo unit, NEST research building, Empa, Dübendorf, Switzerland.

In the case of Chennai, New Delhi, Hong Kong and Haikou (Chandrasekaran et al., 2025), 6-14% cooling-load savings were reported, while in Darwin, 5-15.5% cooling-load savings were reported (Mohammed et al., 2022). The amount of savings is greatly influenced by the glass or glazing behind the device. The cooling energy savings due to shading for a low-energy triple glazing office in Kuala Lumpur, Malaysia, were found to be 1.0-3.4% annually for each façade, and 5-10% for all façades when shading was applied (Lau et al., 2016). The four adaptive façade families were compared in terms of their ability to reduce annual thermal loads, and it was found that dynamic shading and EC glazing have the greatest impact, up to 30% (Attia et al., 2022). Less frequently, embodied impacts are taken into account. High-performance internal blinds demonstrated up to 70% lower embodied carbon over a 60-year lifespan compared to external aluminium venetian blinds, and similar or better energy performance in a Zurich office building (Bonatesta et al., 2025). The widely held belief that external aluminium louvres are always the most sustainable choice should be challenged.

OPEN ACCESS © CINEFORUM

4. CROSS-SYSTEM SYNTHESIS

4.1. Operational energy

The 27 studies that reported operational-energy outcomes are summarized in Figure 9. Three observations are as follows:

The range of each system is as great as the range between systems. The savings for DSFs are about 8-42%, for EC glazing they are 5-36%, for ventilated cladding they are 7-55% and for textile skins they are 20-35%. Nothing is better than anything else, unless you have a context.

The headline number is primarily dependent on the reference case. The same EC glazing has an over 45% reduction compared with single glazing but approximately 20% reduction compared to code compliant glazing (Sbar et al., 2012), and shading is less effective in front of low-e glass (Lau et al., 2016).

Climate compatibility is crucial. Buffer-type systems (DSFs, double membranes) are better suited to heating-dominated climates while solar-interception systems (external shading, ventilated cladding) are better suited to cooling-dominated climates.

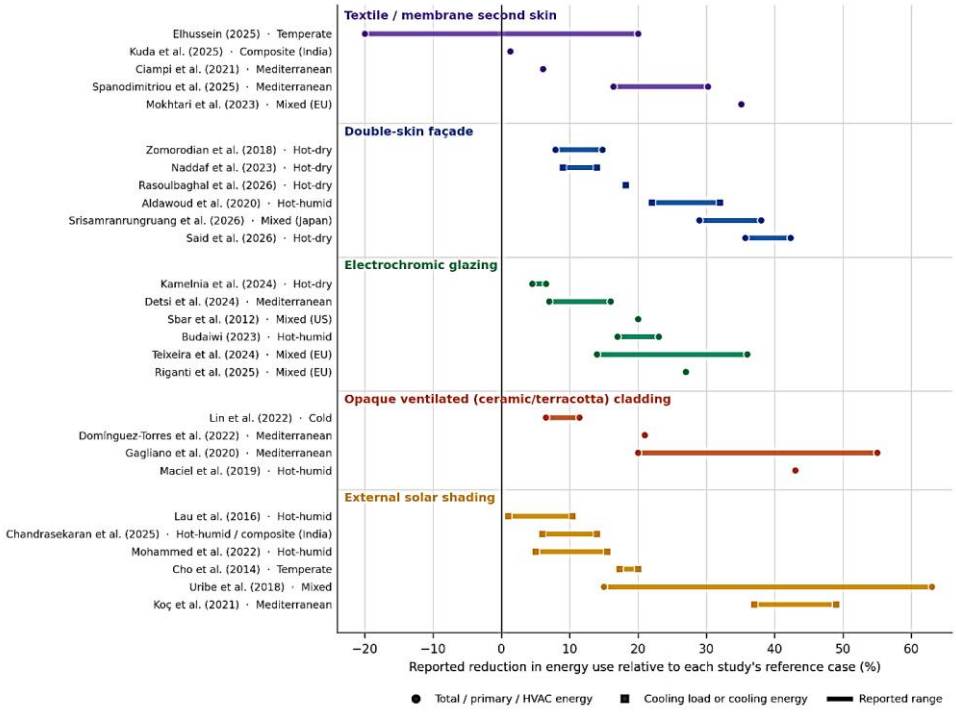


Figure 9. Operational-energy reductions reported for the façade systems reviewed (combined ceramic and terracotta cladding) by study and climate. Bars represent the range of values reported and single points represent individual values. Circles = total, primary or HVAC energy, squares = cooling load or cooling energy. Demand decreases if the value is below 0. This is due to differences in reference cases and metrics across studies which prevent direct comparisons of results.

4.2. Embodied carbon and circularity

The carbon embodied in the envelope and the carbon used in operation are mutually conflicting and very sensitive to the local climate and the carbon intensity of the grid. In low carbon grids, over-investment in envelope material can result in more than 10 $kgCO_2e/m^2$; under-investment can result in over 150 $kgCO_2e/m^2$ in carbon-intensive grids (Echenagucia et al., 2022). In a near zero energy office (NZEO) embodied impacts were increased by 10% while operational energy was reduced by 8.3% by the use of enhanced glazing (Feehan et al., 2021). The highest production related emission factors can be found for aluminium frames. The life-cycle CO_2 of each square metre of glazing was nearly 30% greater than that of the same area of opaque wall (Radhi et al., 2012).

The curtain walls generated greater net benefits for extending service life and reusing at end-of-life (EOL) than for recycling (Cheong et al., 2024). Under carbon pricing, optimal solutions moved from aluminium intensive systems (at approximately 380-400 $kgCO_2e/m^2$) to timber-hybrid systems (at approximately 270-300 $kgCO_2e/m^2$), (Motalebi et al., 2026). In a systematic review of 122 studies, 13 circular design strategies and 24 indicators of circularity for façades were identified, while no standardised method for evaluating the circularity was found (Alabdulrazzaq et al., 2025). The circularity scores varied between 21-28% for traditional façade systems, and 35-77% for bio-based systems, with the scores being influenced more by design for disassembly than by the actual

OPEN ACCESS © CINEFORUM

material itself (Alabdulrazzaq et al., 2026). However, practitioners cite inadequate take-back infrastructure and a lack of separation technology as challenges to façade re-use (Hartwell et al., 2021). A comparative life-cycle assessment compared the life-cycle energy and emissions of a transparent composite façade to that of uncoated glass curtain wall and determined that the former used 93% of the emissions and 89% of the energy. In that study the use phase dominated (Kim, 2011).

4.3. Multi-criteria evidence matrix

Table 1 summarises the evidence for each system against eight criteria. Ratings indicate the direction and consistency of the evidence reviewed, not a weighted score. Weights must be set for each project, climate and client brief (Moghtadernejad et al., 2018).

Table 1. Multi-criteria evidence matrix.

Criterion	Textile / membrane	Double-skin façade	Electrochromic glazing	Ceramic / terracotta OVF	External shading
Operational energy, hot climates	◐ conditional	◐ conditional; risk of overheating	● consistent savings	● consistent savings	● consistent savings
Operational energy, cold/temperate climates	◐ double layers help	● consistent savings	◐ moderate	◐ moderate	◐ may raise heating demand
Thermal comfort	○ low inertia, high PPD	◐ depends on cavity control	◐ little effect on PPD	● reduces surface temperatures	● reduces overheating
Daylight and visual comfort	◐ depends on openness	◐ depends on outer skin	◐ control-dependent; gloom risk	n/a (opaque)	● with perforated louvres
Embodied carbon	◐ low mass, high per kg	○ +23–47%	○ high (glass, frames)	◐ sub-frame and firing energy	◐ high for aluminium
Durability and maintenance	◐ optical decay of foils reported	◐ cavity cleaning, controls	◐ controls, switching cycles	● durable cladding	◐ moving parts if kinetic
Circularity / end of life	◐ recyclable ETFE; PVC poor	◐ dry assembly possible	○ laminated, hard to separate	● mechanically fixed, reusable	● mechanically fixed
Cost evidence	◐ low capital, replacement	○ long payback in hot climates	◐ falling; control costs	◐ moderate	● short payback reported

Note. ● = supported by consistent evidence; ◐ = conditional or mixed evidence; ○ = evidence indicates a weakness; n/a = not applicable.

4.4. Common claims compared with evidence

Table 2 contrasts claims frequently encountered in practice-oriented façade literature with the peer-reviewed evidence reviewed above.

Table 2. Common claims about façade materials compared with peer-reviewed evidence.

Claim	Verdict	Evidence
Fabric façades reflect solar heat and act as a thermal jacket in winter.	Conditional	Depends on openness, coating and stand-off; uniform mesh application increased demand by 20% (Elhussein, 2025); low thermal inertia (Tian et al., 2021).
Membrane installation cost is up to 50% lower.	Not found in peer-reviewed sources	Lower capital cost than masonry reported for sports halls (Ranđelović et al., 2026), but no verified percentage for façades.

OPEN ACCESS © CINEFORUM

Claim	Verdict	Evidence
Double-skin façades reduce heat and improve comfort.	Conditional	Effective in temperate climates; in hot climates needs ventilation and shading, embodied carbon 23-47% (Hashemi et al., 2010; Zomorodian et al., 2018).
Glass panels reduce energy consumption by up to 35%.	Misattributed	35.57% achieved only with EC glazing, BIPV and energy management combined (Fathi et al., 2021); EC alone typically 7–27% against code glazing.
Ceramic and clay tiles are excellent heat insulators.	Incorrect as stated	Benefit arises from the ventilated cavity, reflectance and outer insulation (Roig et al., 2024; Gagliano et al., 2020).
External aluminium louvres are the most sustainable shading.	Conditional	Large operational savings (Koç et al., 2021), but external aluminium blinds can carry up to 70% more embodied carbon than high-performance internal blinds (Bonatesta et al., 2025).

4.5. Selection guidance by climate

The evidence has been used to support the guidance below for early stage façade selection in high-rise buildings:
Climates that are hot and dry, or hot and humid: Opt for solar interception before glass façade (external shading/perforated screens) and ventilated opaque cladding to the east and west façade. Do not use DSFs without cavity ventilation, shading in cavity and night purging. Don't use single layer membranes in occupied areas.
Climates of composite and monsoon: Use shading from outdoors as well as moderate window-to-wall ratio, incorporating fixed external shading to suit summer sun angles.
To keep views, open on west sides, consider EC glazing but not with glare control - temperature control.
Temperate and cold climates: Double membranes and EC glazing can provide heating and cooling savings as can DSFs. Shading must be adjustable so as to not incur heating penalties in the winter.
All climates: Report reference case, WWR (Window to wall ratio), control strategy with any savings claims, embody carbon, service life, and end-of-life re-use with EN 15978-type life cycle boundaries.

5. DISCUSSION

There are three major conclusions to draw from this systematic literature review. First, the sustainability of any façade is the function of the building façade in relation to the particular context of use rather than a characteristic of any specific building materials. A terracotta panel, a glass pane, and a PTFE membrane may all become components of either an energy-saving façade or a very high-energy façade depending on climate, location, details of its design and operation. Second, the majority of studies are simulation based. More precisely, most of the articles in this systematic review were based on simulations using EnergyPlus, TRNSYS, IES-VE or CFD tools; only few studies used real-life field data (Fantucci et al., 2020; Hashemi et al., 2010; Lin et al., 2022). The same is true for reviews of DSFs and smart façades (Habibi et al., 2022; Pomponi et al., 2016). Hence, savings obtained via simulation are potential savings rather than actual savings. Third, embodied carbon becomes more and more important. When operational energy is reduced, the materials, structure, and replacement cycle of facades become a greater proportion of the total lifetime carbon dioxide emissions (Alabdulrazzaq et al., 2026; Cheong et al., 2024). Those systems which have a double layer of glass and aluminum may lose the advantage of operation energy when embodied carbon is included into the calculations (Srisamranrungruang et al., 2026; Zomorodian et al., 2018). Durable, mechanically attached and reusable systems such as ventilated ceramic facade or shading systems have an advantage in this field. However, this applies only when the design for disassembly approach is applied (Celadyn et al., 2025; Hartwell et al., 2021).
The high-rise specific problems including wind loads, fire safety of cladding and membranes, and maintenance access were not considered in this literature review. These factors have to be taken into account anyway before applying any system mentioned above.

6. CONCLUSIONS

This paper reviewed the available scientific evidence on six types of façade materials that are being used in high rise buildings. Six conclusions were drawn from the review:
All the six façade material systems can save operational energy; however, the amount varies from 20% increment to 63% decrement. This is mainly due to the climate, orientation, glazing ratio, control and reference.
Buff-type facade material systems (double-skin and double layer systems) are suitable for heating-dominated climates. In hot climates, they need cavity ventilation and shading to avoid overheating.

OPEN ACCESS © CINEFORUM

Solar interception systems (shading devices and ventilated ceramic and terracotta cladding) give the highest saving consistently in cooling-dominated climates. The benefit is provided by the system itself rather than by its insulation property.
Electro-chromic glazing can save cooling peaks and glare if used properly controlled. The saving value is largely dependent on reference glazing; the generally cited 35% saving only refers to technological package.
Embodied carbon, lifespan, and reuse at end-of-life can overturn the order implied by operational energy. The façade choice must thus involve whole-life, multi-criteria evaluation.
The designer should regard manufacturers' performance claims as hypotheses that can be tested against site-specific simulations and life-cycle analysis, together with disclosure of reference case and boundary conditions for any claimed savings.

DECLARATIONS

Funding. This research received no specific grant from any funding agency in the public, commercial or not-for-profit sectors.
Conflict of interest. The authors declare no competing interests.
Declaration of generative AI and AI-assisted technologies in the writing process. The authors used Consensus (an AI-assisted academic search engine) to identify and screen peer-reviewed literature, and Claude (Anthropic) to assist with structuring the review, drafting and editing the manuscript text. After using these tools, the authors reviewed and edited all content, verified every cited source and take full responsibility for the content of the publication..

REFERENCES

1. Ahriz, A., et al. (2022). The use of double-skin façades to improve the energy consumption of high-rise office buildings in a Mediterranean climate (Csa). Sustainability, 14, 6004.
2. https://doi.org/10.3390/su14106004
3. Aksamija, A. (2013). Sustainable facades: Design methods for high-performance building envelopes. Wiley.
4. Alabdulrazzaq, H., et al. (2025). A framework for circular facade design: Systematic review of design strategies and performance indicators. Journal of Cleaner Production.
5. https://doi.org/10.1016/j.jclepro.2025.147140
6. Alabdulrazzaq, H., et al. (2026). Comparative study of conventional and emerging façade systems: Pathways to reducing embodied carbon and enhancing circularity in buildings. Energy and Buildings. https://doi.org/10.1016/j.enbuild.2026.117778
7. Aldawoud, A., et al. (2020). Double skin façade: Energy performance in the United Arab Emirates. Energy Sources, Part B: Economics, Planning, and Policy. https://doi.org/10.1080/15567249.2020.1813845
8. Attia, S., et al. (2022). Comparison of thermal energy saving potential and overheating risk of four adaptive façade technologies in office buildings. Sustainability, 14, 6106. https://doi.org/10.3390/su14106106
9. Bal, Y., et al. (2026). A new perspective in life cycle assessment enhanced by principal component analysis: A comparative case study of facade materials for sports and event building envelope. Ain Shams Engineering Journal. https://doi.org/10.1016/j.asej.2026.104399
10. Bianchi, S., et al. (2024). Multi-criteria design methods in façade engineering: State-of-the-art and future trends. Building and Environment. https://doi.org/10.1016/j.buildenv.2024.111184
11. Bonatesta, E., et al. (2025). Keeping cool with lower emissions: Comparing internal to external blinds as solar shading devices. IOP Conference Series: Earth and Environmental Science, 1554, 012115. https://doi.org/10.1088/1755-1315/1554/1/012115
12. Budaiwi, I. (2023). Assessing the energy-saving potential and visual comfort of electrochromic smart windows in office buildings: A case study in Dhahran, Saudi Arabia. Sustainability, 15, 9632. https://doi.org/10.3390/su15129632
13. Castillo-DR, R., et al. (2026). Thermal performance evaluation of a double skin façade with latticework solar protection: A case study in a humid tropical climate (Panama). Energy and Buildings. https://doi.org/10.1016/j.enbuild.2025.116747
14. Celadyn, M., et al. (2025). Durability of building facades and sustainable architecture. Sustainability, 17, 9569. https://doi.org/10.3390/su17219569
15. Chandrasekaran, C., et al. (2025). Energy savings from the shading performance of devices in highly glazed multi-story office buildings in the tropical climates of China and India. Journal of Chinese Architecture and Urbanism. https://doi.org/10.36922/jcau025120026
16. Cheong, C., et al. (2024). Life cycle assessment of curtain wall facades: A screening study on end-of-life scenarios. Journal of Building Engineering. https://doi.org/10.1016/j.jobe.2024.108600

OPEN ACCESS © CINEFORUM

17. Cho, J., et al. (2014). Viability of exterior shading devices for high-rise residential buildings: Case study for cooling energy saving and economic feasibility analysis. Energy and Buildings. https://doi.org/10.1016/j.enbuild.2014.07.092
18. Ciampi, G., et al. (2021). Energy performance of PVC-coated polyester fabric as novel material for the building envelope: Model validation and a refurbishment case study. Journal of Building Engineering. https://doi.org/10.1016/j.jobe.2021.102437
19. Day, J. K., et al. (2019). Blinded by the light: Occupant perceptions and visual comfort assessments of three dynamic daylight control systems and shading strategies. Building and Environment. https://doi.org/10.1016/j.buildenv.2019.02.037
20. Detsi, M., et al. (2024). Effect of smart glazing with electrochromic and thermochromic layers on building's energy efficiency and cost. Energy and Buildings. https://doi.org/10.1016/j.enbuild.2024.114553
21. Domínguez-Torres, C.-A., et al. (2022). Empirical and numerical analysis of an opaque ventilated facade with windows openings under Mediterranean climate conditions. Mathematics, 10(1), 163. https://doi.org/10.3390/math10010163
22. Dussault, J.-M., et al. (2017). Office buildings with electrochromic windows: A sensitivity analysis of design parameters on energy performance, and thermal and visual comfort. Energy and Buildings. https://doi.org/10.1016/j.enbuild.2017.07.046
23. Echenagucia, T. M., et al. (2022). On the tradeoffs between embodied and operational carbon in building envelope design: The impact of local climates and energy grids. Energy and Buildings. https://doi.org/10.1016/j.enbuild.2022.112589
24. Elhussein, S. (2025). The multi-objective optimisation for energy consumption and daylight of office buildings in London: Meshed façade energy study. World Journal of Science, Technology and Sustainable Development, 20(4), 297–337. https://doi.org/10.47556/j.wjstsd.20.4.2025.1
25. Fantucci, S., et al. (2020). An experimental sensitivity analysis on the summer thermal performance of an opaque ventilated façade. Energy and Buildings. https://doi.org/10.1016/j.enbuild.2020.110354
26. Fathi, S., et al. (2021). Effect of electrochromic windows on energy consumption of high-rise office buildings in different climate regions of Iran. Solar Energy. https://doi.org/10.1016/j.solener.2021.05.021
27. Feehan, A., et al. (2021). Adopting an integrated building energy simulation and life cycle assessment framework for the optimisation of facades and fenestration in building envelopes. Journal of Building Engineering. https://doi.org/10.1016/j.jobe.2021.103138
28. Gagliano, A., et al. (2020). Analysis of the energy performance of an opaque ventilated façade under winter and summer weather conditions. Solar Energy. https://doi.org/10.1016/j.solener.2020.05.078
29. Habibi, S., et al. (2022). Sustainability performance by ten representative intelligent façade technologies: A systematic review. Sustainable Energy Technologies and Assessments. https://doi.org/10.1016/j.seta.2022.102001
30. Hamza, N. (2007). Double versus single skin facades in hot arid areas. Energy and Buildings. https://doi.org/10.1016/j.enbuild.2007.02.025
31. Hartwell, R., et al. (2021). Circular economy of façades: Real-world challenges and opportunities. Resources, Conservation and Recycling. https://doi.org/10.1016/j.resconrec.2021.105827
32. Hashemi, N., et al. (2010). Thermal behaviour of a ventilated double skin façade in hot arid climate. Energy and Buildings. https://doi.org/10.1016/j.enbuild.2010.05.019
33. Jelle, B. P., et al. (2019). Comparison of the energy saving potential of adaptive and controllable smart windows: A state-of-the-art review and simulation studies of thermochromic, photochromic and electrochromic technologies. Solar Energy Materials and Solar Cells. https://doi.org/10.1016/j.solmat.2019.02.041
34. Kamelnia, H., et al. (2024). Enhancing daylight performance and visual comfort in office buildings with electrochromic glazing: A case study of Mashhad. Iranica Journal of Energy and Environment. https://doi.org/10.5829/ijee.2025.16.01.16
35. Kim, K. (2011). A comparative life cycle assessment of a transparent composite façade system and a glass curtain wall system. Energy and Buildings. https://doi.org/10.1016/j.enbuild.2011.09.006
36. Koç, S., et al. (2021). The effects of shading devices on office building energy performance in Mediterranean climate regions. Journal of Building Engineering. https://doi.org/10.1016/j.jobe.2021.102653
37. Kuda, A., et al. (2025). Performance of PTFE-based adaptive building facades for climate resilience: A simulation-driven analysis. International Journal of Engineering, Science and Information Technology. https://doi.org/10.52088/ijesty.v5i4.1071
38. Lamnatou, C., et al. (2018). Ethylene tetrafluoroethylene (ETFE) material: Critical issues and applications with emphasis on buildings. Renewable and Sustainable Energy Reviews. https://doi.org/10.1016/j.rser.2017.08.072

OPEN ACCESS © CINEFORUM

39. Lau, A., et al. (2016). Potential of shading devices and glazing configurations on cooling energy savings for high-rise office buildings in hot-humid climates: The case of Malaysia. International Journal of Sustainable Built Environment. https://doi.org/10.1016/j.ijsbe.2016.04.004
40. Lin, Z., et al. (2022). An experimental study of the summer and winter thermal performance of an opaque ventilated facade in cold zone of China. Building and Environment. https://doi.org/10.1016/j.buildenv.2022.109108
41. Maciel, A. C. F., et al. (2019). Operational energy of opaque ventilated façades in Brazil. Journal of Building Engineering. https://doi.org/10.1016/j.jobe.2019.100775
42. Mainini, A., et al. (2022). On the optical characterization of architectural three-dimensional skins and their solar control potential. Buildings, 12, 1103. https://doi.org/10.3390/buildings12081103
43. Moghtadernejad, S., et al. (2018). Multi-criteria decision-making methods for preliminary design of sustainable facades. Journal of Building Engineering. https://doi.org/10.1016/j.jobe.2018.05.006
44. Mohammed, A., et al. (2022). Reducing the cooling loads of buildings using shading devices: A case study in Darwin. Sustainability, 14, 3775. https://doi.org/10.3390/su14073775
45. Mokhtari, N., et al. (2023). Textile as second-skin façade for building envelope retrofitting: A numerical analysis on the comfort, energy and environmental impacts in different European climates. Building Simulation Conference Proceedings. https://doi.org/10.26868/25222708.2023.1484
46. Monticelli, C., et al. (2020). Material saving and building component efficiency as main eco-design principles for membrane architecture: Case-studies of ETFE enclosures. Architectural Engineering and Design Management. https://doi.org/10.1080/17452007.2020.1768507
47. Motalebi, M., et al. (2026). Integrated BIM–LCA–optimization for decarbonizing curtain wall façades under carbon pricing uncertainty. Building Research & Information. https://doi.org/10.1080/09613218.2026.2653037
48. Naddaf, M., et al. (2023). The role of double-skin facade configurations in optimizing building energy performance in Erbil city. Scientific Reports, 13. https://doi.org/10.1038/s41598-023-35555-0
49. Palmero-Marrero, A. I., et al. (2010). Effect of louver shading devices on building energy requirements. Applied Energy. https://doi.org/10.1016/j.apenergy.2009.11.020
50. Pizzatto, F., et al. (2025). Ventilated facade system: A review. Boletín de la Sociedad Española de Cerámica y Vidrio. https://doi.org/10.1016/j.bsecv.2025.100443
51. Pomponi, F., et al. (2016). Energy performance of double-skin façades in temperate climates: A systematic review and meta-analysis. Renewable and Sustainable Energy Reviews. https://doi.org/10.1016/j.rser.2015.10.075
52. Prieto, A., et al. (2024). What is your building doing for the city? Systematic literature review on the potential of façade design for the mitigation of urban environmental problems. Sustainability, 16, 7855. https://doi.org/10.3390/su16177855
53. Radhi, H., et al. (2012). Global warming implications of facade parameters: A life cycle assessment of residential buildings in Bahrain. Environmental Impact Assessment Review. https://doi.org/10.1016/j.eiar.2012.06.009
54. Ranđelović, D., et al. (2026). Climate-specific performance of textile membrane sports halls: Energy efficiency, comfort, and economic assessment via EnergyPlus. Textiles, 6, 72. https://doi.org/10.3390/textiles6020072
55. Rasoulbaghal, M., et al. (2026). Evaluating passive and active cooling strategies in double-skin façades for hot, arid climates. Journal of Renewable and Sustainable Energy. https://doi.org/10.1063/5.0281924
56. Riganti, M., et al. (2025). Energy saving potential of advanced dual-band electrochromic smart windows for office integration. Energy and Buildings. https://doi.org/10.1016/j.enbuild.2024.115084
57. Roig, O., et al. (2024). Opaque ventilated façades: Energy performance for different main walls and claddings. Energy and Buildings. https://doi.org/10.1016/j.enbuild.2024.114280
58. Said, M. A., et al. (2026). Multiobjective optimization of double-skin façade performance using XGBoost and NSGA-II in buildings under hot climate conditions. International Journal of Energy Research. https://doi.org/10.1155/er/7007403
59. Saroglou, T., et al. (2020). Studies on the optimum double-skin curtain wall design for high-rise buildings in the Mediterranean climate. Energy and Buildings. https://doi.org/10.1016/j.enbuild.2019.109641
60. Sbar, N., et al. (2012). Electrochromic dynamic windows for office buildings. International Journal of Sustainable Built Environment. https://doi.org/10.1016/j.ijsbe.2012.09.001
61. Shafaghat, A., et al. (2022). Dynamic façades design typologies, technologies, measurement techniques, and physical performances across thermal, optical, ventilation, and electricity generation outlooks. Renewable and Sustainable Energy Reviews. https://doi.org/10.1016/j.rser.2022.112647
62. Sheweka, S. M., & Mohamed, N. M. (2012). Green facades as a new sustainable approach towards climate change. Energy Procedia, 18, 507–520. https://doi.org/10.1016/j.egypro.2012.05.062

OPEN ACCESS © CINEFORUM

63. Spanodimitriou, Y., et al. (2025). Evaluating the performance of fixed 3D-printed and dynamic fabric modules in a second-skin façade system: A residential case study in Southern Italy at building and district scales. Buildings, 15, 189. https://doi.org/10.3390/buildings15020189
64. Srisamranrungruang, T., et al. (2026). Life carbon assessment of embodied and operational carbon with view assessment across facade systems in Japanese climate zones. Results in Engineering. https://doi.org/10.1016/j.rineng.2026.109219
65. Stazi, F., et al. (2020). The role of wall layers properties on the thermal performance of ventilated facades: Experimental investigation on narrow-cavity design. Energy and Buildings. https://doi.org/10.1016/j.enbuild.2019.109622
66. Suo, H., et al. (2015). Thermal-physical behavior and energy performance of air-supported membranes for sports halls: A comparison among traditional and advanced building envelopes. Energy and Buildings. https://doi.org/10.1016/j.enbuild.2015.10.011
67. Tabadkani, A., et al. (2020). Design approaches and typologies of adaptive facades: A review. Automation in Construction. https://doi.org/10.1016/j.autcon.2020.103450
68. Takva, F. G., et al. (2026). Multi-parameter thermal performance and investment cost analysis of opaque ventilated facades in hot-humid climates. Architectural Engineering and Design Management. https://doi.org/10.1080/17452007.2026.2722977
69. Teixeira, H., et al. (2024). Simulation-based evaluation of the impact of an electrochromic glazing on the energy use and indoor comfort of an office room. Energies, 17, 2110. https://doi.org/10.3390/en17092110
70. Tian, G., et al. (2021). Indoor thermal environment of thin membrane structure buildings: A review. Energy and Buildings. https://doi.org/10.1016/j.enbuild.2020.110704
71. Uribe, D., et al. (2018). Potential of perforated exterior louvers to improve the comfort and energy performance of an office space in different climates. Building Simulation. https://doi.org/10.1007/s12273-018-0435-y
72. Zomorodian, Z., et al. (2018). Energy and carbon analysis of double skin façades in the hot and dry climate. Journal of Cleaner Production. https://doi.org/10.1016/j.jclepro.2018.06.178

OPEN ACCESS © CINEFORUM